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Modeling In-Cylinder Water Injection in a 2-Stroke Internal Combustion Engine

Mohamed I. Hassan*, Ayoola T. Brimmo

Department of Mechanical and Materials Eng., Masdar Institute of Science and Technology, P.O.Box 54224, Abu Dhabi, UAE

Abstract

In this study, we apply Computational Fluid Dynamics (CFD) models in investigating the effect of injecting water into the combustion chamber of a 2-stroke Internal Combustion Engine (ICE). Using the commercial code, Star-CD, 3-D models for a port scavenging, in-cylinder fuel-injection; 2-Stroke engine is developed. The adapted engine's effective compression ratio (CR), crank Revolution per Minute (RPM) and fuel type are 8.5, 2000 rpm and Heptane (C_7H_{16}) respectively. Two types of water mixing techniques are investigated: homogenous pre-mixing with the reactants, and direct injection around the walls of the combustion chamber. The engine's pressure, temperature, and pollutant mass fraction are estimated as a function of crank angle and injected water to fuel mass ratio, for both mixing techniques. The calculated indicated work (area under P-V diagrams) is used to estimate other engine performance indicated parameters. Results showed that although the homogenous mixing of water has an effect of reducing the combustion temperature and resulting NO_x emissions, the pressure exerted on the piston is greatly diminished by this technique. However, when water vapor is injected around the chamber walls, the resulting reduction in temperature and NO_x emissions has a minimum effect on the engine's P-V diagram. This is as a result of a water vapor blanket formed around the combustion zone, by the injected water vapor, which cools down the cylinder's wall with a minimum influence on the combustion process. Further analysis showed that the water injection technique could increase the power/torque per engine size and hence, increase energy efficiency. Ultimately, the study presents the advantages of using water injection for enhancing fuel efficiency and reducing pollutant emissions

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1. Introduction

In light of the increased stringency in fuel economy and greenhouse gas (GHG) regulations like the Cooperate Average Fuel Economy (CAFE) in the United States, automobile manufacturers have to revisit fuel consumption and GHG emission reduction techniques. In the literature, there are numerous in-cylinder strategies for reducing emissions and enhancing fuel efficiency. Among these, Exhaust gas recirculation (EGR) is the most widely adapted and studied. In diesel engines, the use of EGR allows exhaust NO_x emissions to be reduced substantially, while in Spark Ignition (SI) engines, reduction in brake specific fuel consumption can also be achieved [1]. However, the decrease of NO_x emissions with EGR is the result of complex and sometimes opposite phenomena occurring during combustion [2, 3]. Furthermore, EGR increases particulate matter (PM) emissions in the classical high temperature Diesel combustion and requires an increase in boost pressure, at middle and high loads, while maintaining air–fuel ratio (AFR) at a suitable level [4].

An alternative in-cylinder strategy for achieving lower engine emissions is the injection of water into the combustion chamber. The method of supplying water to the combustion chamber of engines has been known for a long

* Corresponding author. Tel.: +971 2 810 9332;

E-mail address: miali@masdar.ac.ae.

time [1], two decades ago, Mitsubishi produced a water injection system for a direct-injection (DI) diesel engine [6]. The primary intent of this technique is to lower the exhaust gas temperature and hence achieve a reduced NOx emission. The most common ways of introducing water into the combustion chamber includes injection at the inlet manifold [7, 8, 9, 10], mixing with the fuel charge [11, 12, 13] and direct injection in the combustion chamber [14, 6]. Previous studies indicate that regardless of the water injection technique, the introduction of water clearly reduces NOx emissions [6-14]. In some cases, this reduction was observed to be comparable to that achieved by EGR applied on the same engine [8]. However, while some studies have reported minimal effect of water injection on the in-cylinder pressure and heat release rate of the engine [7], others have reported a work reduction [6]. Most of the studies in this line have been done experimentally [4, 6, 7, 8, 10, 11, 12, 14]. Only a few computational studies have been come across [15, 16, 13] with majority based on 2-D models and none considering a wide range of fuel. Taking into account the complexity and investment cost involved in conducting such experiments, the use of computational tools, which allows for greater flexibility, offers a quick and effective alternative to optimizing the benefits of water injection in ICEs. Only with these tools would it be economically feasible to investigate water injection strategies that enhance fuel economy as well as reduce pollutant emissions, for a wide range of fuels and engine design.

In the present study, we demonstrate the use of CFD in investigating the effect of water injection techniques on the pollutant emissions and performance of a 2-stroke Compression Ignition (CI) engine. Two water injection techniques were considered: homogenous premixing and direct combustion chamber injection. The development of these models is achieved by effecting an interaction between the physical equations which describe the fluid dynamics and chemical kinetics of the reacting gases. These models were developed using the commercial code, Star-CD.

2. Methodology

A dome-shaped piston-cylinder setup of a 2 stroke engine workbench model is developed on Star-CD. The utilized geometry is designed to present the following advantages: absence of valves, presence of loop-flow scavenging, and capability of generating tangential flow to enhance flow circulation and hence increase the flow residence time in the cylinder. Figure 1 shows the single cylinder engine geometry with the generated mesh. The charge and exhaust ports are placed on the lower circumference of the engine cylinder. A 100 mm diameter cylinder is adapted with a piston effective stroke of 45mm with an effective compression ratio of 8.5. Four rectangular inlet ports (2 horizontal and 2 tilted by 45 degree) are implemented, each with a height of 12.5mm and a width of 20mm. Three squared exhaust port with 25 mm side are attached to one side of the cylinder. The premixed water mixing technique is modeled by homogenous vapor mixing with the inlet charge, while the combustion chamber injection technique is modeled by injecting water from 8 injectors, at the top circumference of the cylinder. For the direct combustion chamber injection technique, the water injection starts at 10 Crank Angle Degrees (CAD) before the Top Dead Center (TDC) and lasts over a period of 30 CAD. For both techniques, the in-cylinder average gases temperature, pressure and pollution emission are estimated as a function of the mass of water vapor injected. This mass of injected water is indicated as a ratio to the fuel's mass i.e.

$$\text{Mass ratio of injected water} = m_w/m_f \quad (1)$$

Where m_w and m_f are the masses of injected water and fuel respectively.

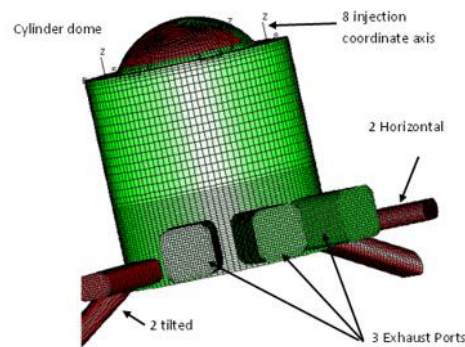


Figure 1: Geometry and 3-D discretization of the model

3. Results

Figure 2 (a) shows the average in-cylinder temperature as function of the piston's crank angle and mass ratio of water vapor homogeneously mixed with the reactants. As expected, when water vapour is not mixed with the reactants ($m_w/m_f=0$), the in-cylinder temperature rises to about 2400K few degrees just after the TDC and then gradually decreases during the expansion process. This peak temperature correlates well with the flame temperature of the Heptane fuel [3]. A similar trend is observed when the water vapor is mixed homogeneously with mass ratios of 1 and 2. However, the post combustion in-cylinder temperature reduces as the water mass ratio increases. This can be attributed to the effect of introduced water vapor in increasing the heat capacity of the burned gasses as the mass of premixed water vapor increases. This trend correlates well with the percentage reduction in NO emission with diluent water mass presented in reference [17].

The reduction in peak combustion temperature observed in Figure 2 (a) has significantly reduced the NO emission as shown in Figure 2 (b). The NO formation at a water mass ratio of 2 is negligible. This is expected as according to the Zeldovich mechanism for NO formation, the rate coefficient for the $O + N_2 \rightarrow NO + N$ reaction rapidly reduces at temperatures below 1800K [3]. The effect of the premixed water vapour on the cylinder pressure and work indicator diagram (P-V), are shown in

Figure 3 (a) and (b) respectively. Diluting the reactants with water vapour has a great impact on the peak pressure and engines performance (as indicated in the P-V diagram). This is as a result of the reactants dilution with the water vapour that causes a significant effect of reducing the combustion strength which is also indicated in the peak in-cylinder temperature as shown in Figure 2 (a). The cylinder temperature reduces as the mass ratio of water vapour increases.

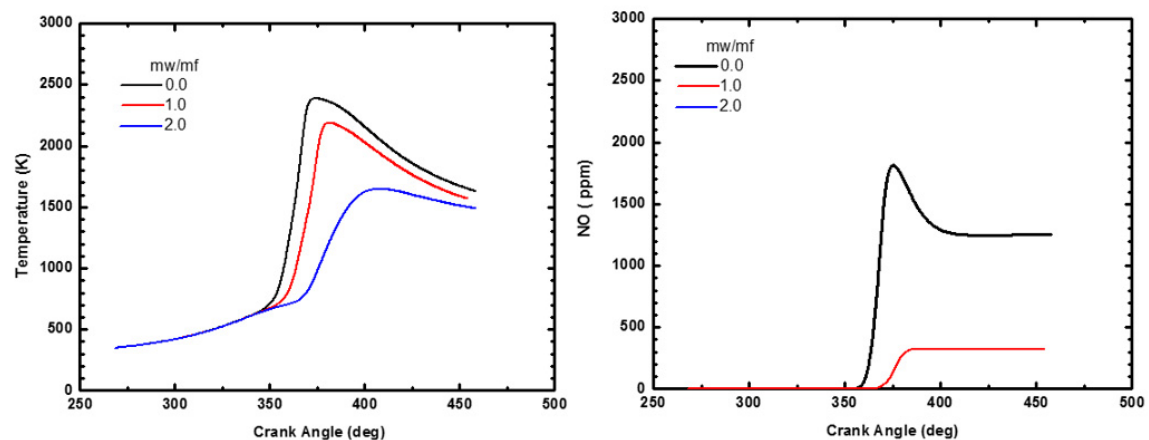


Figure 2: Homogeneously mixed water vapour technique (a) Cylinder average temperature; (b) NO emission

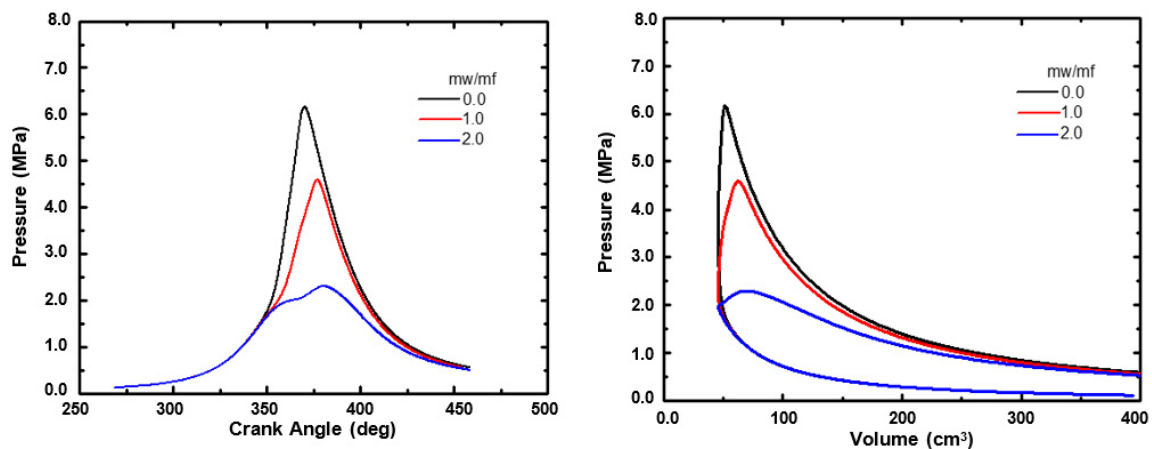


Figure 3: Homogeneously mixed water vapour technique (a) Cylinder pressure; (b) P-V diagram

Figure 4 (a) shows the combustion temperature as a function of crank angle and the mass fraction of the water vapour, using the direct combustion chamber injection method. The combustion temperature reduces as the mass fraction of water vapour increases. However, at a water mass fraction of 8, the combustion process failed to proceed.

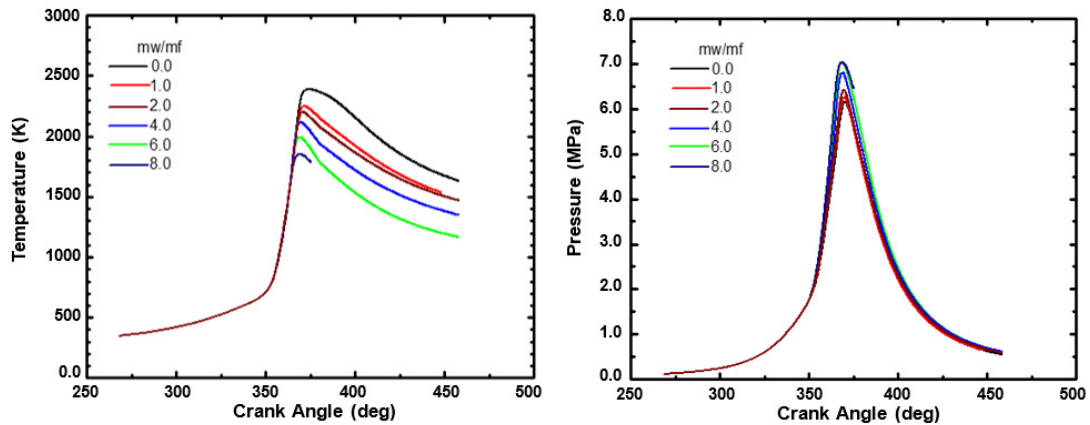


Figure 4: Water injection technique (a) Cylinder average temperature; (b) Cylinder pressure

The temperature reduction can be attributed to the water vapour blanket developed around the cylinder's wall as suggested by Figure 5 and Figure 6 – which show the cylinder side wall's (Figure 5a), cross section (Figure 5b) and top walls temperature profiles (Figure 6b), and the volume of fluid across the cylinder (Figure 6a), as water is injected. From these, it can be inferred that the heat absorbed due to water evaporation is transferred from the combustion gases hence, reducing the average cylinder temperature. However, the combustion process' peak pressure does not significantly change as the mass ratio of injected water increases, as shown in Figure 4 (b). As the water is injected just before the piston reaches the TDC, it is not given enough time to mix with the reactant and hence does not significantly affect the combustion process. The slight increment in peak pressure observed in Figure 4 (b), as the mass ratio of injected water vapour increases, can be attributed to the contribution of water vapour volume expansion. Therefore, water injection aided reduction in the combustion gases' temperature. Also, the expansion due to the phase change contributed in maintaining the cylinder pressure. The reduction in combustion temperature has an effect of reducing the NO and CO emissions as shown in Figure 7 (a) and (b) respectively. In other words, water injection avoids the dilution of the reactants to maintain the flame propagation strength, absorbs heat from the products to reduce the peak temperature and hence reduces the pollutant emissions with maintaining the cylinder pressure.

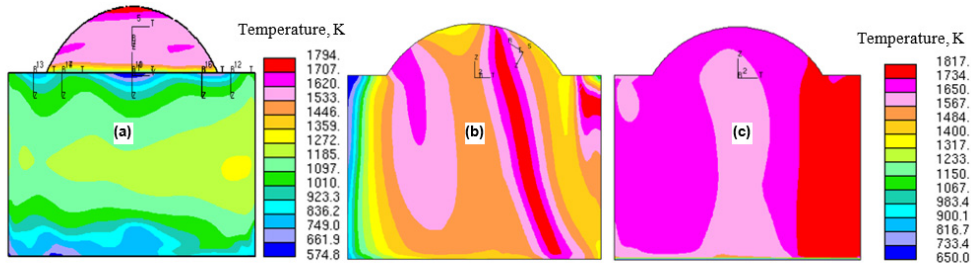


Figure 5: Vertical view, Temperature contours at 90 CAD after TDC; (a) cylinder walls for mw/mf=4.0, (b) cross section for mw/mf=4.0, (c) cross section for mw/mf=0.0

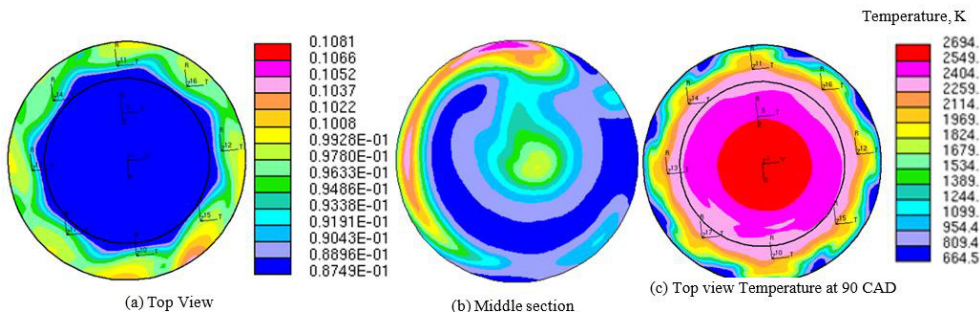


Figure 6: Injected water VOF and temperature profiles; Horizontal sections at 90 CAD for mw/mf=4

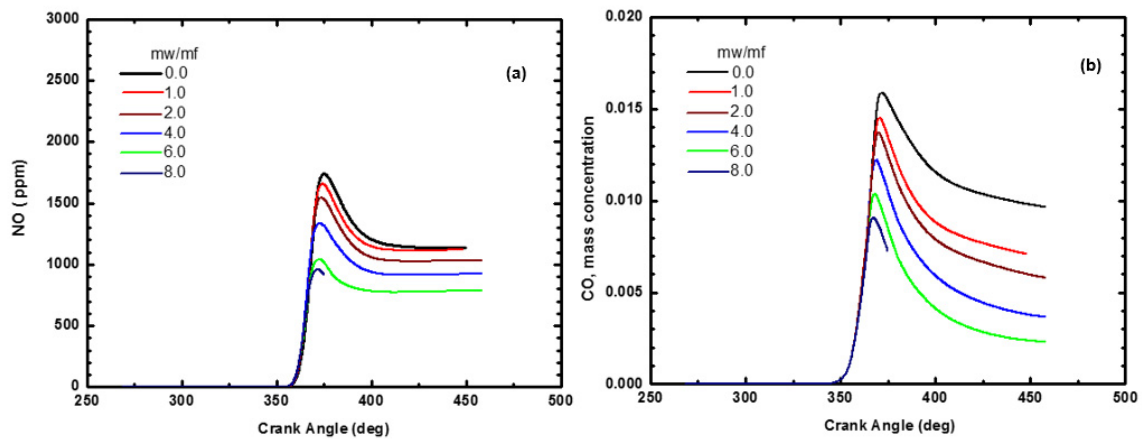


Figure 7: (a) NO emission as function of crank angle and injected water mass ratio; (b) CO mass concentration as a function of crank angle and injected water vapour mass ratio.

Evaluating the engine's thermal efficiency (η_{th}), Indicated Specific Fuel Consumption (ISFC), Indicated Power (IP), and torque, slight enhancements in engine performance is observed as the mass ratio of injected water increases. Comparing the engine with no water injection with that of a water mass ratio of 6, directly injected in the combustion chamber, the thermal efficiency is increased from 45.66% to 46.04%, ISFC reduces from 0.1792 to 0.1777, IP increases from 36.1kW to 36.4kW, and the engine torque increases from 172.5N-m to 173.9N-m. If we count for the uncertainty, there is no change in the engine indicated parameters while the main goal of emission reduction is achieved.

Further studies to optimize the water vapour injection time and period are expected to additionally increase the benefits of this technique. Optimization of the injection location could also be beneficial in further enhancement of the engine's performance.

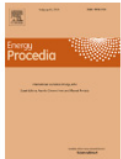
4. Conclusion

CFD models of a 2-stroke engine were developed, on the commercial code, Star-CD, to investigate the effect of water vapor premixing and water direct in-cylinder injection, on the engines performance and pollutant emission. Results show that diluting the reactants with water has a significant effect of reducing the in-cylinder average gases temperature and hence, NO emissions. This effect increases as the mass of premixed water vapor increase. However, the premixed water vapor has an effect of diminishing the combustion strength. On the other hand, injecting water directly into the combustion chamber at 10 CAD before the TDC, over a period of 30 CAD, reduces the in-cylinder average gas temperature and pollutant emission while slightly increasing the engine's performance. Optimization of the water vapor injection time is expected to further increase engine performance.

References

- [1] G.H. Abd-Alla, "Using exhaust gas recirculation in internal combustion engines: a review," *Energy Conversion and Management*, vol. 43, no. 8, p. 1027–1042, 2002.
- [2] J.B. Heywood, *Internal combustion engine fundamentals*, New York: McGraw-Hill, 1988.
- [3] S.R. Turns, *An introduction to combustion: Concepts and Applications*, United States: McGraw- Hill, 2000.
- [4] Xavier Tauzia, Alain Maiboom and Samiur R. Shah, "Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine," *Energy*, vol. 35, no. 9, p. 3628–3639, 2010.
- [5] Lars Sandberg and Bjorn Scheuer, "Turbo charged combustion engine with water injection". United States Patent US 4558665 A, 17 December 1985.

- [6] S. Brusca and R. Lanzafame, "Evaluation of the effects of water injection in a single cylinder CFR cetane engine," *SAE Technical Paper*, no. 2001-01-2012, 2001.
- [7] B. Tesfa, R. Mishra, F. Gu and A.D Ball, "Water injection effects on the performance and emission characteristics of a CI engine operating with biodiesel," *Renewable Energy*, vol. 31, no. 7, pp. 333-344, 2012.
- [8] S. Shah, A. Maiboom, X. Tauzia and J. Hétet, "Experimental Study of Inlet Manifold Water Injection on a Common Rail HSDI Automobile Diesel Engine, Compared to EGR with Respect to PM and Nox Emissions and Specific Consumption," *SAE Technical Paper*, no. 2009-01-1439, 2009.
- [9] D. Hountalas, G. Mavropoulos, T. Zannis and S. Mamalis, "Use of water emulsion and intake water injection as NOx reduction techniques for heavy-duty diesel engines.," *SAE Technical Paper*, no. 2006-01-1414, 2006.
- [10] M. Musculus, J. Dec., D. Tree and D. Daly, "Effects of Water-Fuel Emulsions on Spray and Combustion Processes in a Heavy-Duty DI Diesel Engine," *SAE Technical Paper*, no. 2002-01-2892, 2002.
- [11] I. C. Jeong and K. H. Lee, "Auto-ignition and micro-explosion behaviors of droplet arrays of water-in-fuel emulsion," *International Journal of Automotive Technology*, vol. 9, no. 6, pp. 735-740, 2008.
- [12] M. Selim and M. Ghannam, "Performance and Engine Roughness of a Diesel Engine Running on Stabilized Water Diesel Emulsion," *SAE Technical Paper*, no. 2007-24-0132, 2007.
- [13] F. Bedford, C. Rutland, P. Dittrich and A. e. a. Raab, "Effects of Direct Water Injection on DI Diesel Engine Combustion," *SAE Technical Paper*, no. 2000-01-2938, 2000.
- [14] M. Psota, W. Easley, T. Fort and A. Mellor, "Water Injection Effects on NOx Emissions for Engines Utilizing Diffusion Flame Combustion," *SAE Technical Paper*, no. 971657, 1997.
- [15] Nader Larbi and Jamel Bessrou, "Measurement and simulation of pollutant emissions from marine diesel combustion engine and their reduction by water injection," *Advances in Engineering Software*, vol. 41, no. 6, p. 898–906, 2010.
- [16] M. H. Badr, M. I. Hassan and A.A. EL-Hamalawy, "On Demand Hydrogen Cell for Automobile Fuel Consumption Efficiency," *International Journal of Green Energy*, vol. Accepted, 2014.
- [17] K. Komiyama and J.B. Heywood, "Predicting NOx emissions and effects of Exhaust gas Recirculation in spark ignition engines," *SAE Paper*, no. 730475, 1973.



Biography

Mohamed Ibrahim Hassan Ali is assistant professor in the mechanical and materials engineering department of Masdar Institute of Science and Technology. Dr. Ali earned his PhD in mechanical power engineering on a channel program between the University of Helwan, Cairo, Egypt, and the University of Michigan, Ann Arbor, Michigan, USA.